

# Effects of various types of reflectors on the $^{99}\text{Mo}$ production in the VVER-Ts reactor targets<sup>\*</sup>

Oleg Yu. Kochnov<sup>1</sup>, Pavel A. Danilov<sup>2</sup>

1 JSC “NRFChI n.a. L.Ya. Karpov”, 6 Kievskoye shosse, Obninsk, Kaluga Reg., 249033 Russia

2 Obninsk Institute for Nuclear Power Engineering, NRNU “MEPhI”, 1 Studgorodok, Obninsk, Kaluga Reg., 249040 Russia

Corresponding author: Oleg Yu. Kochnov (kochnov2000@mail.ru)

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## Abstract

The effects from introducing various types of reflectors in the VVR-Ts reactor core on the  $^{99}\text{Mo}$  production were analyzed. Earlier the effects of only the beryllium reflector on the VVR-Ts reactor core characteristics, such as reactivity margin, neutron flux in experimental channels, and activity of the accumulated  $^{99}\text{Mo}$ , were calculated. The calculations are based on a generated precision model of the core which comprises one experimental channel where targets are irradiated for the  $^{99}\text{Mo}$  production. The model was built using the SCALE code. The code allows a fairly broad range of calculations to be performed, from criticality estimation to radiological assessment tasks. As the result of the computational analysis of the model, such characteristics were obtained as the effective multiplication factor, the power density in the  $^{99}\text{Mo}$  production targets, the neutron flux in the target raw material, and the quantity of the produced  $^{99}\text{Mo}$  after 120 hours of irradiation. The data was compared with the results of similar calculations of the VVR-Ts reactor core parameters. Further, the list of the materials used extensively as the reactor core reflector or moderator was formed based on reference literature. A number of models were obtained and analyzed on its basis, in which the water space on the core periphery was substituted for the investigated materials.

## Keywords

VVR-Ts reactor, reflector,  $^{99}\text{Mo}$  production, neutron flux, power density, SCALE code

## Introduction

At the present time,  $^{99}\text{Mo}$  is produced in the VVR-Ts reactor in the forcedly cooled vertical experimental channels which accommodate two targets of the tube-in-tube type placed one on the other. The outer diameter is 36 mm and the fuel portion height is 150 mm. Each of the targets is designed as two tubes between which there is a mixture of  $\text{U}_3\text{O}_8$  and  $\text{ZnO}$  (Kochnov and Kolesov 2012). Such configuration has proved to be more efficient for the  $^{99}\text{Mo}$  production than the previous version (“sleeve-in-sleeve”).

As shown by the calculation results, the power density in the channel, with the targets of the new type loaded into it, was 32.9 kW which is 1.7 as high as with the loaded targets of the old design (Kochnov et al. 2012).

The effects of the beryllium reflector on the  $^{99}\text{Mo}$  production have been calculated, and the calculation results are presented in (Kochnov et al. 2013). Depending on the beryllium layout in the core, the calculations showed that the  $^{99}\text{Mo}$  production increased by at least 2% and by 9% at the greatest. The effects of the beryllium reflector on the VVR-Ts reactor core parameters were analyzed in

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(Kochnov and Kolesov 2012, Kolesov et al. 2015). The calculation results showed a major increase in the reactor reactivity margin and up to a 10% flux growth in the experimental channels.

The optimization of the  $^{99}\text{Mo}$  production was analyzed proceeding from the possibility of increasing the number of the experimental channels in the core. It was shown in the process of the studies that the "...placement of beryllium blocks in six cavities on the core periphery makes it possible to install one more experimental channel for the radionuclide production without reconfiguring the rest of the core and without affecting greatly the reactivity characteristics of the CPS rods" (Kochnov et al. 2018).

The  $^{99}\text{Mo}$  production in the VVER-Ts reactor can be increased by redesigning the target. A new target design, which contains much starting material, was proposed as the result of a computational analysis. It has been proved that the new design satisfies the allowable thermal-hydraulic parameters in the experimental channel. The investigation results are provided in (Kochnov et al. 2019, Fomin et al. 2017, Kolmykov et al. 2018a, b, c, d, Kolmykov and Zevyakin 2019).

The purpose of the work is to compare the effects of various reflector materials on the  $^{99}\text{Mo}$  production increase in the VVER-Ts reactor. Such type of calculations for the VVER-Ts reactor core was performed earlier only for the beryllium reflector, but no comparative analysis against other types has been conducted. Resolving this issue will make it possible to select the most effective reflector material from the list of the materials analyzed for producing the maximum possible quantity of  $^{99}\text{Mo}$  after irradiation in the reactor core. The selection of the reflector material was based on the extent of its application as the reflector in nuclear power. The properties of extensively used reflectors and moderators are described in detail in (Bobkov et al. 2012) based on which the reflector materials were selected.

## Initial data

The power density in the experimental channels was calculated using the SCALE code (Rearden and Jessee 2016), in which the model was analyzed with the use of two modules, KENO-VI and ORIGEN. The former calculates the core parameters using Monte Carlo method. The latter calculates the burn-up based on the numerical solution of a system of differential equations which describe the formation, depletion, and decay of nuclides (Rearden and Jessee 2016):

$$\frac{dN_i}{dt} = \sum_{j \neq i} (l_{ij}\lambda_j + f_{ij}\sigma_j\Phi)N_j(t) - (\lambda_i + \sigma_i\Phi)N_i(t) + S_i(t), \quad (1)$$

where  $N_i$  is the quantity of the nuclide  $i$ ;  $\lambda_i$  is the decay constant of the nuclide  $i$ ;  $l_{ij}$  is the yield of the nuclide  $i$  in the decay of the nuclide  $j$ ;  $\sigma_i$  is the spectrum-averaged removal cross-section for the nuclide  $i$ ;  $f_{ij}$  is the yield of the nuclide  $i$  in the burn-up of the nuclide  $j$ ;  $\Phi$  is the angle and

energy integrated neutron flux; and  $S_i$  is the time-dependent source.

Based on data in (Kochnov et al. 2012, Kolesov et al. 2011, 2014), a precision model of the VVER-Ts reactor core was formed with an experimental channel where  $^{99}\text{Mo}$  is produced (Figs 1, 2).

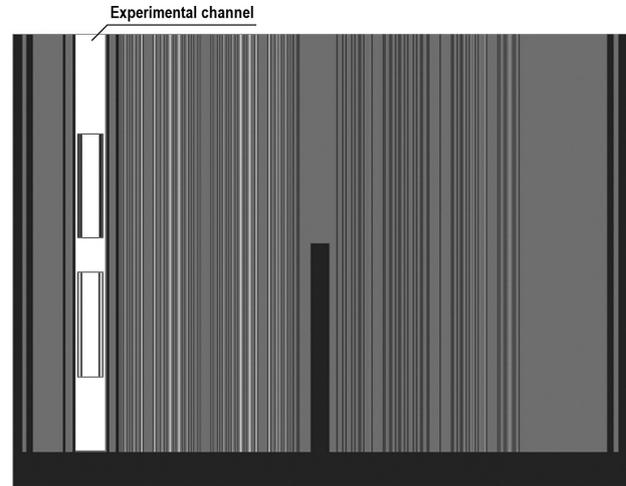


Figure 1. A vertical cut of the VVER-Ts reactor model.

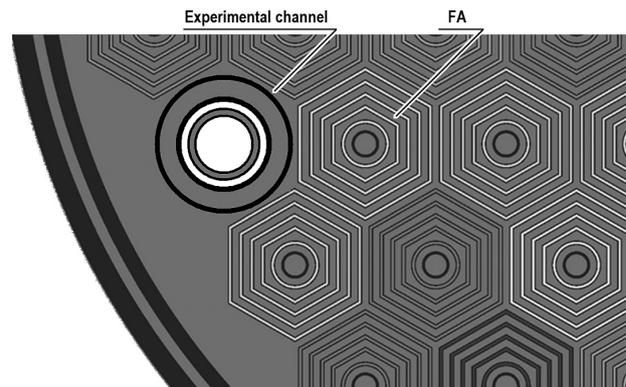


Figure 2. A horizontal cut of a VVER-Ts reactor portioz.

To check the adequacy of the model built and the computation parameters, the following key characteristics were calculated: the effective multiplication factor, the neutron flux in the target material, and the power density in the targets. The automatic control (AC) and manual control (MC) rods in the computational model are half-submerged in the core. For KENO-VI, 750 neutron generations of 10000 neutrons each were selected as the parameters. The power of the model was rated for 10 MW in the fuel portions of all FAs. The obtained data was compared with the results of the calculations for a similar model in the MCNP code.

## Calculations

Table 1 presents the results from the calculation of the power density in the upper target and in the lower target

**Table 1.** Comparison of the obtained target characteristics in the SCALE and MCNP codes.

Code	Characteristics			
	Neutron flux in upper target, n/(cm <sup>2</sup> s)	Neutron flux in lower target, n/(cm <sup>2</sup> s)	Power density in upper target, kW	Power density in lower target, kW
SCALE	(1.28±0.02)·10 <sup>14</sup>	(1.36±0.02)·10 <sup>14</sup>	16.0±0.2	17.1±0.2
MCNP	(1.31±0.01)·10 <sup>14</sup>	(1.39±0.01)·10 <sup>14</sup>	16.0±0.2	16.9±0.2

and of the neutron flux in these, as well as the respective values obtained in (Kochnov et al. 2012).

The effective multiplication factor, as calculated using the SCALE code, is  $k_{\text{eff}} = 1.01041 \pm 0.00026$ . In (Kochnov et al. 2012),  $k_{\text{eff}} = 1.01097 \pm 0.00034$ . The calculation results for the effective multiplication factor, the neutron flux, and the power density in the target material converge with the data in (Kochnov et al. 2012) within the uncertainty limits.

The most widely used moderators in nuclear power (graphite, beryllium, beryllium oxide, zirconium hydride) were selected as the reflector material. The reflector is situated along the side surface of the core. In the existing reactor core design, the region, where the reflectors were introduced, is filled with water.

The density and isotope composition data for the graphite reflector calculation were taken for the VPG and SGT graphite grades. VPG is the most widely used graphite grade in reactor industry and the SGT graphite has the highest density thanks to the silicon saturation.

Table 2 presents data on the isotope composition and density of the considered reflector types. The material data was taken from (Bobkov et al. 2012).

**Table 2.** Reflector characteristics.

Material	Density, kg/m <sup>3</sup>	Isotope composition
VPG graphite	1680	<sup>12</sup> C-98,93%; <sup>13</sup> C-1,07%
SGT graphite	2500	<sup>12</sup> C-49,465%; <sup>13</sup> C-0,535%; <sup>28</sup> Si-46,115%; <sup>29</sup> Si-2,335%; <sup>30</sup> Si-1,55%
Beryllium oxide	2200	<sup>9</sup> Be, <sup>16</sup> O
Zirconium hydride	5600	<sup>90</sup> Zr-51,45%; <sup>91</sup> Zr-11,22%; <sup>92</sup> Zr-17,15%; <sup>94</sup> Zr-17,38%; <sup>96</sup> Zr-2,8%; <sup>1</sup> H
Beryllium	1848	<sup>9</sup> Be-100%

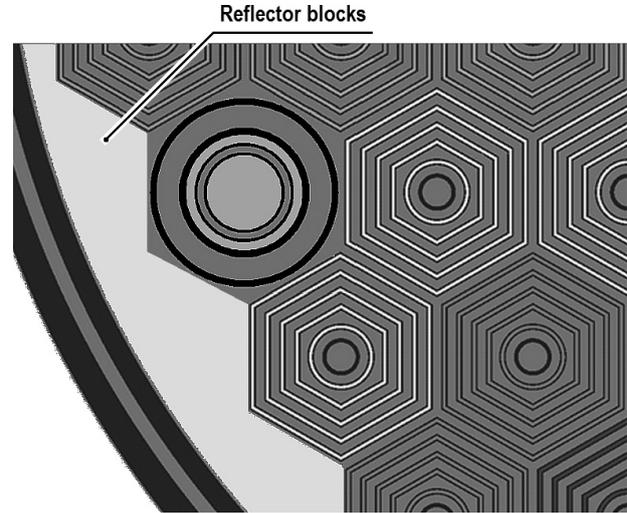
The reflector blocks are situated on the core periphery filling all of the cavities between the reactor side wall and the peripheral FAs (Fig. 3). Table 3 presents calculated values of the neutron fluxes and power densities in the target material at the initial time.

**Table 3.** Calculation of the power density and neutron flux in the experimental channel for various reflector types.

Reflector material in cavities	Neutron flux, 10 <sup>14</sup> n/(cm <sup>2</sup> s)		Power density, kW	
	Lower target	Upper target	Lower target	Upper target
VPG graphite	1.39±0.02	1.30±0.02	16.4±0.2	15.3±0.2
SGT graphite	1.40±0.02	1.31±0.02	16.2±0.2	15.1±0.2
Beryllium oxide	1.44±0.02	1.33±0.02	17.2±0.2	15.8±0.2
Zirconium hydride	1.35±0.02	1.26±0.02	16.5±0.2	15.6±0.2
Beryllium	1.47±0.02	1.39±0.02	17.7±0.2	16.7±0.2

**Table 4.** Activity of <sup>99</sup>Mo as of the irradiation end time.

Reflector	Beryllium	Beryllium oxide	Zirconium hydride	SGT graphite	VPG graphite	Water
Activity of produced <sup>99</sup> Mo, 10 <sup>13</sup> Bq	4.55±0.09	4.37±0.09	4.29±0.09	4.14±0.08	4.25±0.09	4.37±0.09

**Figure 3.** Experimental channel with reflector blockz.

The activity of the produced <sup>99</sup>Mo from the two targets after 120 hours of irradiation with various reflector materials in the core is presented in Table 4.

According to the calculation results for the power density and activity of <sup>99</sup>Mo in the targets, the introduction of only the beryllium reflector will increase the production as compared with the existing design in which the reflector region is filled with water. The activity of the produced <sup>99</sup>Mo in this case is 4% higher which is confirmed by the similar value in (Kochnov et al. 2013).

## Conclusion

A precision model of the VVR-Ts reactor core has been formed which can be used for computational studies in future. The results of calculating the key characteristics of the VVR-Ts reactor core have a good fit with earlier results. The calculation of the power density and the <sup>99</sup>Mo production with various reflectors used on the core periphery has shown that it is only the beryllium reflector that contributes greatly to the production increase as compared with the water reflector. The activity of the produced <sup>99</sup>Mo after 120 hours of irradiation, when the beryllium reflector is used, is 4% as high as the value when the water reflector is used. Estimates show that other reflector types have worse or similar parameters.

## References

- Bobkov VP, Blokhin AI, Zabudko LM, Kazantsev GN, Romyantsev VN, Smogalev IP, Tarasikov VP (2012) Handbook of Material Properties for Advanced Reactor Technologies (Vol. 4). Properties of Moderators. Ed. by Prof. V.M. Poplavsky. Moscow. Izdat Publ., 408 pp. [in Russian]
- Fomin RV, Kolesov VV, Zevyakin AS, Kochnov OYu (2017) Estimation of the  $^{99}\text{Mo}$  production increase using advanced design targets in the VVR-ts reactor. Proc. of the 2<sup>nd</sup> International Conference of Young Scientists, Specialists and Post-Graduate Students “Innovative Small and Super Small Nuclear Reactors”, 15–17 May. Rosatom State Corporation, National Research Nuclear University “MEPhI”. Moscow. NIYaU MIFI Publ.: 14–15. [in Russian]
- Kochnov OYu, Kolesov VV (2012) Effects of the beryllium reflector placed in the VVR-ts reactor core on its neutronic performance. Izvestiya Vysshikh Uchebnykh Zavedeniy. Yadernaya Energetika, 2: 22–125. [in Russian]
- Kochnov OYu, Kolesov VV, Fomin RV (2012) Estimation of the power density in targets with a uranium containing material for production of  $^{99}\text{Mo}$  using advanced design targets in the VVR-ts reactor. Izvestiya Vysshikh Uchebnykh Zavedeniy. Yadernaya Energetika, 4: 23–29. <https://doi.org/10.26583/npe.2012.4.03> [in Russian]
- Kochnov OYu, Kolesov VV, Fomin RV (2013) Estimation of the  $^{99}\text{Mo}$  production increase with various core layouts in the VVR-ts reactor. Izvestiya Vysshikh Uchebnykh Zavedeniy. Yadernaya Energetika, 1: 110–147. <https://doi.org/10.26583/npe.2013.1.14> [in Russian]
- Kochnov OYu, Kolesov VV, Fomin RV, Fomichenko PA (2018) The possibility for increasing the number of the VVR-ts experimental channels by means of the core redesign. Atomnaya Energiya, 125(3): 146–147. <https://doi.org/10.1007/s10512-018-00460-7> [in Russian]
- Kochnov OYu, Kolesov VV, Fomin RV, Zherdev GM (2014) Estimation of the increase in the  $^{131}\text{I}$  production using tellurium targets of an improved design in the VVR-ts Reactor. Izvestiya Vysshikh Uchebnykh Zavedeniy. Yadernaya Energetika, 4: 102–110. <https://doi.org/10.26583/npe.2014.4.11> [in Russian]
- Kochnov OYu, Kolesov VV, Zevyakin AS, Fomin RV (2019) Thermal-hydraulic calculation of the maximum fuel and water temperature in the MAK-2 Unit. Atomnaya Energiya, 127(3): 135–137. <https://doi.org/10.1007/s10512-020-00601-x> [in Russian]
- Kolesov VV, Kochnov OYu, Fomin RV (2015) Improvement of the VVR-ts neutronic performance by means of replacing some of the core FAs for a beryllium reflector. Atomnaya Energiya, 118(4): 191–193. <https://doi.org/10.1007/s10512-015-9986-5> [in Russian]
- Kolesov VV, Kochnov OYu, Volkov YuV, Ukraintsev VF, Fomin RV (2011) Generation of a precision model of the VVR-ts reactor for the subsequent optimization of its design and for production of  $^{99}\text{Mo}$  and other radionuclides. Izvestiya Vysshikh Uchebnykh Zavedeniy. Yadernaya Energetika, 4: 129–146. [in Russian]
- Kolmykov VYu, Zevyakin AS (2019) Upgrading of the target design for the radioisotope production in the VVR-ts reactor. Proc. of the 14<sup>th</sup> International Scientific and Practical Conference “The Future of Nuclear Power Engineering”, 29–30 November 2018. Obninsk. IATE NIYaU MIFI Publ.: 4–5. [in Russian]
- Kolmykov VYu, Zevyakin AS, Fomin RV (2018d) Upgrading of the target design for the radioisotope production. Proc. of the 2<sup>nd</sup> International (15<sup>th</sup> Regional) Scientific Conference “Man-Made Systems and Ecological Risk”, 19–20 April. Obninsk. IATE NIYaU MIFI Publ.: 15–16. [in Russian]
- Kolmykov VYu, Zevyakin AS, Fomin RV (2018a) Thermal-Hydraulic Calculation of a Rod Type Target for the Radioisotope Production. Proc. of the 3<sup>rd</sup> International Conference of Young Scientists, Specialists, Post-Graduates and Students “Innovative Small and Super Small Nuclear Reactors”, 15–16 May. Obninsk. IATE NIYaU MIFI Publ.: 52–53. [in Russian]
- Kolmykov VYu, Zevyakin AS, Fomin RV, Sobolev AV (2018b) Upgrading of the target design for production of molybdenum. Proc. of the 13<sup>th</sup> International Scientific and Practical Conference “The Future of Nuclear Power Engineering (AtomFuture 2017)”, 27–30 November. Obninsk. IATE NIYaU MIFI Publ.: 8–9. [in Russian]
- Kolmykov VYu, Zevyakin AS, Fomin RV, Sobolev AV (2018c) Comparison of the Thermal-Hydraulic Characteristics of Targets for Molybdenum Production. Proc. of the 7<sup>th</sup> International Youth Scientific School-Conference “Modern Problems of Physics and Technologies”, 16–21 April. Moscow. NIYaU MIFI Publ.: 236–237. [in Russian]
- Rearden BT, Jessee MA (2016) SCALE Code System, ORNL/TM-2005/39, Ver. 6.2.1, Oak Ridge National Laboratory, Oak Ridge, Tennessee. Available from Radiation Safety Information Computational Center as CCC-834.